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Laser Communications to Beam Optical Band to Distant Points

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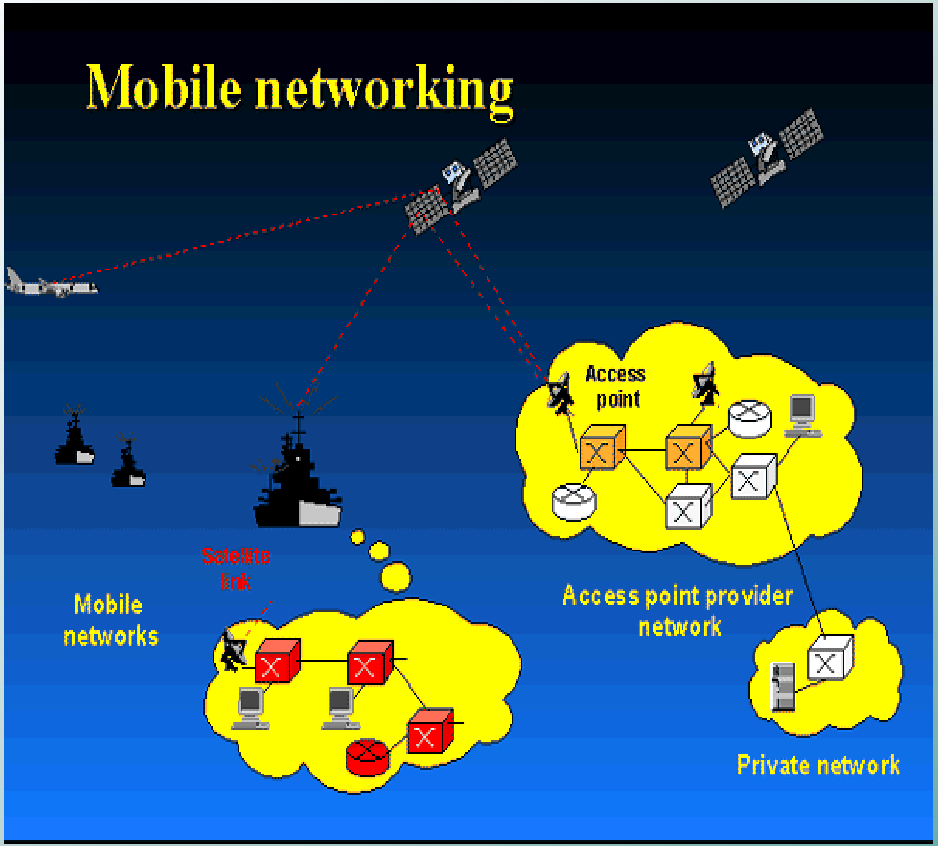
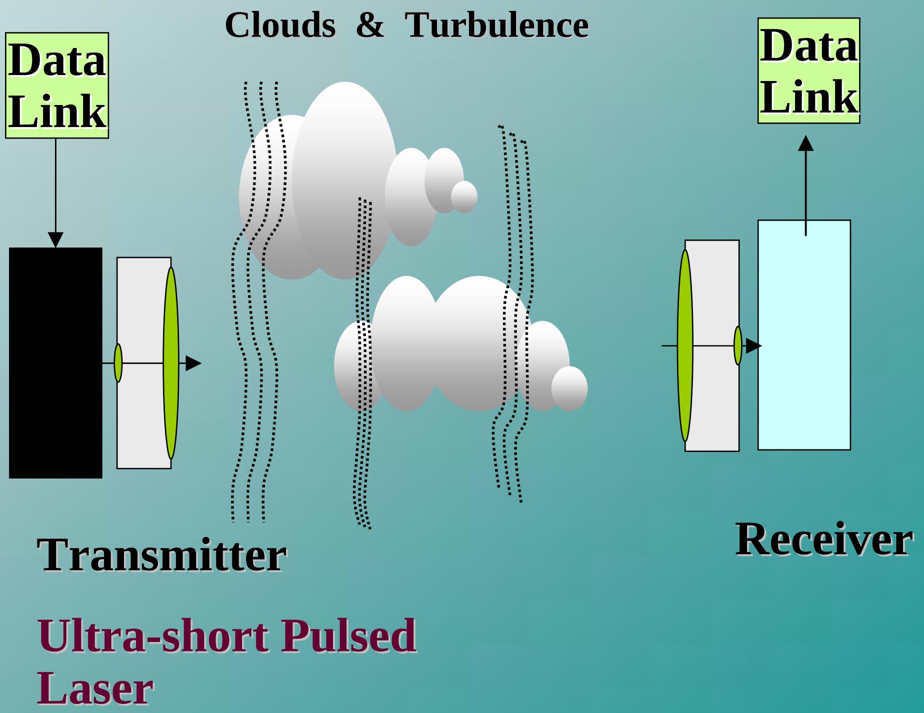
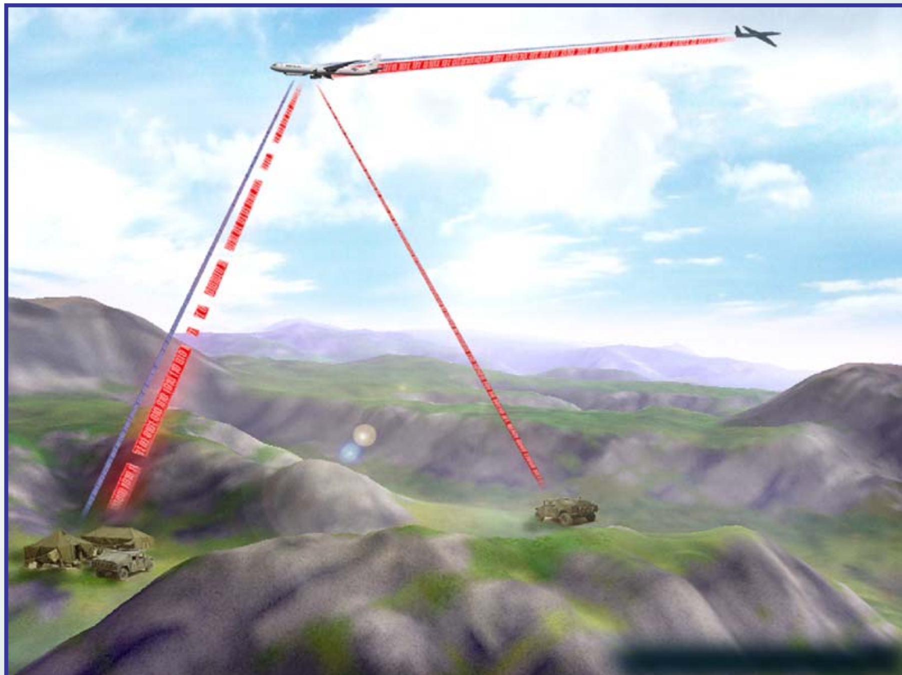
Objectives

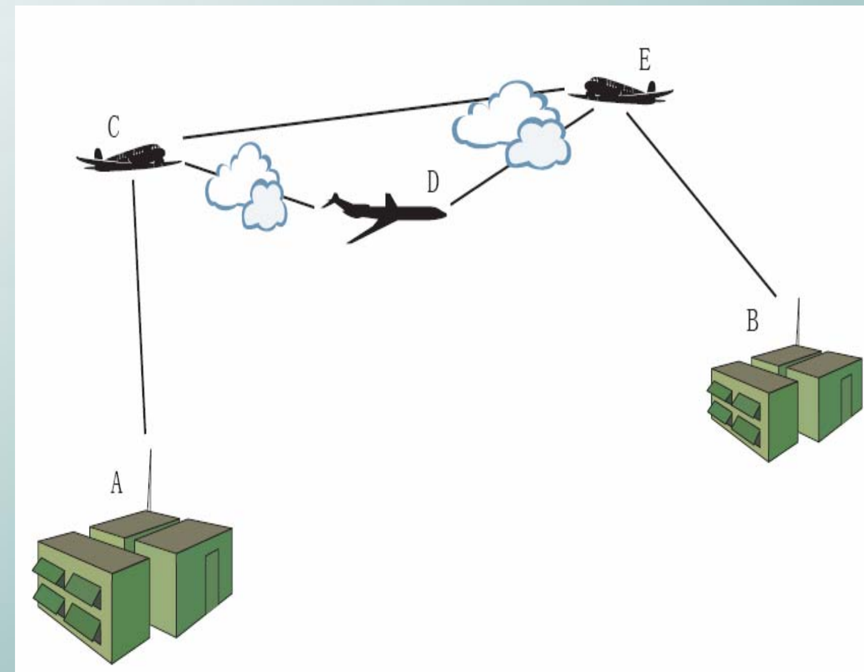
Investigate and demonstrate an Air-to-Air-to-Ground hybrid RF/FSO System, promising a broadband *"See Thru Clouds"*, using ultra-short-pulsed laser link with time/frequency diversity provided by "Fractal Wavelet Modulation" to increase the hybrid link availability and average data rate.





Anti-correlation under Adverse Weather





	Cloud/Fog 	Rain 
FSO	**Severe Attenuation**	**Slight Attenuation**
RF	**Slight Attenuation**	**High Attenuation**

• **M. Kavehrad, " A New Diversity Technique for Interference-Limited Microwave Digital Radios," Canadian Conf. on Elect. and Computer Engineering, Ottawa, Ontario, September 1990.**

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Basics on Clouds

Low Altitude Clouds

100 m – 3.2 km

Cumulus
Stratocumulus
Stratus

Mid Altitude Clouds

3.2 km – 6.5 km

Altocumulus
Altostratus
Nimbostratus

High Altitude Clouds

6.5 km ++

Cirrus
Cirrostratus

Typical Optical thickness for 1 Km

150 ⟷ 1.

Basics on Clouds

Optical thickness τ refers to total optical path length:

$\tau = K_{scat} \,.\, L$, where L is the physical length of channel (cloud chamber).

Cloud Type	k_{scat} (km^{-1})	k_{ext} (km^{-1})
Cumulus	131.8525	133.3700
Stratus	56.8025	57.2575
Stratus-Stratocumulus	37.45	37.6950
Stratocumulus	44.8275	45.2235
Altostratus	95.024	95.7320
Nimbostratus	80.26	81.0760
Thin Cirrus	0.086585	0.0882
Cirrus	0.811425	1.0164

Clouds Channel Modeling

- Channel modeling is performed using Monte-Carlo Ray Tracing Simulations.
- Each photon / particle *(water droplet)* interaction is governed by the Mie Theory.
- Photons are either absorbed or scattered. Direction of the scattered photons are governed by the scattering phase function.
- Trajectory of a photon in a dispersive channel is tracked from transmitter to receiver.
- Temporal dispersion is due to variations in the path length for different photons;
- Spatial dispersion is due to off-axis propagation.

Clouds Channel Delay Spread / Bandwidth

- A common measure to characterize a communications channel; delay spread (T_d) is defined as the time it takes for the channel parameters to de-correlate with respect to previous channel state. It is measured using the correlation power profile.

- Channel Coherence Bandwidth $\simeq 1 / T_{d.}$

- Delay spread is proportional to receive aperture size, channel length and optical thickness.

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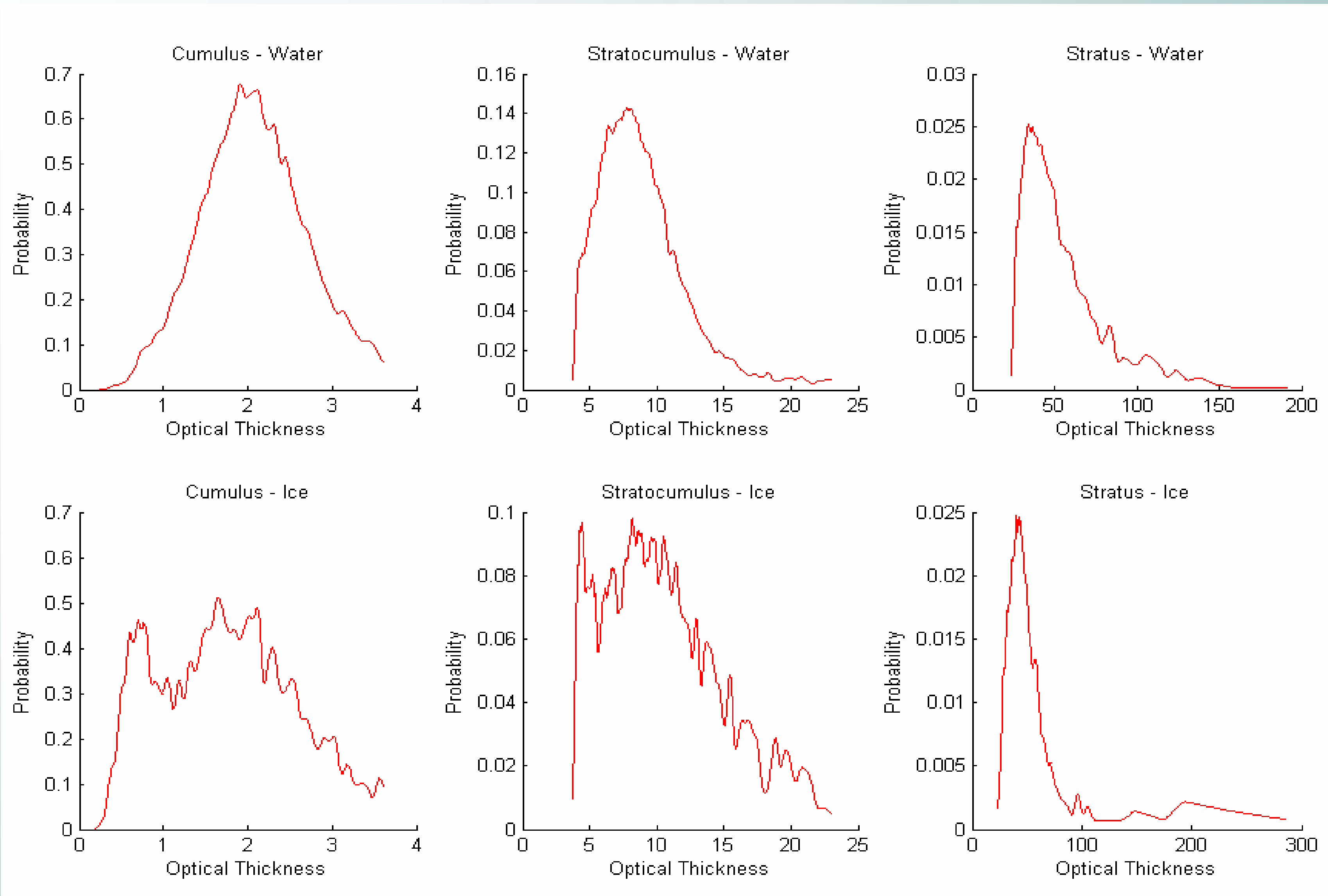
Bandwidth Availability

- Integrating theoretical bandwidth results with statistical cloud information helps estimate the practically available bandwidth in cloud obscured channels.

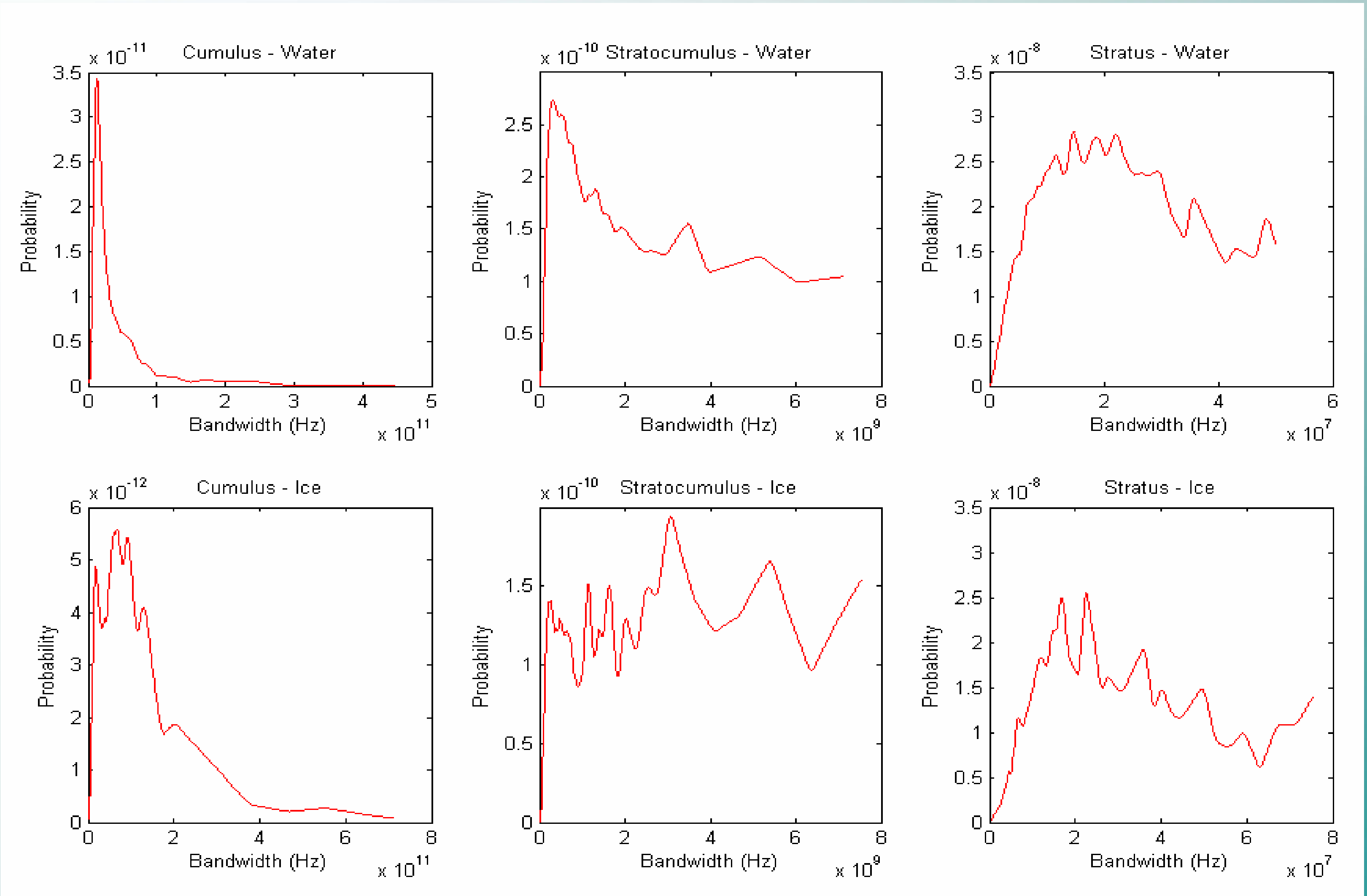
- To evaluate cloud coverage, we use data obtained from the International Satellite Cloud Climatology Project (ISCCP) D1 database.

- The ISCCP database contains cloud information including percentage of spatial coverage and optical thickness for the entire globe. In this database, the globe is divided into 6596 equal size cells, each of which is approximately the area of 2.5° longitude $\times$ 2.5° latitude.

Low Clouds ~ PDF of Optical Thickness; τ



Low Clouds ~ BW PDF



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Results Summary

		Cloud Type	Average τ	Average Bandwidth	Percentage Coverage
Low Altitude	Liquid	Cumulus	2.0521	5.55E+10	0.39384
		Stratocumulus	8.7927	3.00E+09	0.411088
		Stratus	53.262	1.77E+07	0.091564
	Ice	Cumulus	1.6227	1.51E+11	0.061854
		Stratocumulus	10.829	3.99E+09	0.02734
		Stratus	56.228	2.03E+07	0.014314
Medium Altitude	Liquid	Altocumulus	1.8171	1.97E+11	0.165674
		Altostratus	11.732	2.96E+09	0.205437
		Nimbostratus	70.439	2.00E+07	0.127153
	Ice	Altocumulus	1.8703	4.79E+11	0.26428
		Altostratus	11.661	3.72E+09	0.158026
		Nimbostratus	56.157	3.20E+07	0.07943
High Altitude	Ice	Cirrus	1.6255	5.27E+11	0.452862
		Cirrostratus	12.178	9.46E+08	0.345364
		convective	54.112	6.31E+06	0.201774

Av.=3.25E+10

Av.=1.6E+11

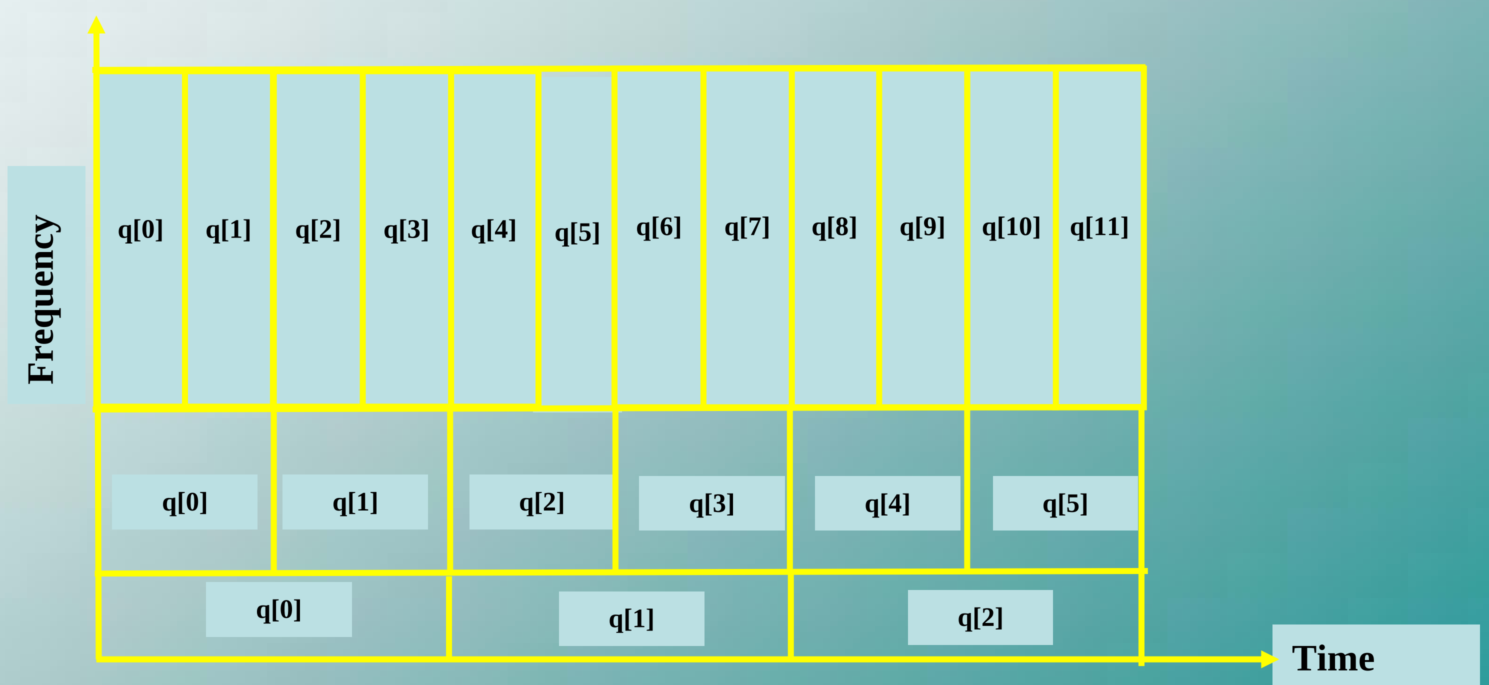
Av.=2.4E+11

Clouds Coherence Bandwidth Results Summary

- Substantial bandwidth is available for communications during typical meteorological conditions, even in the presence of clouds.
- Results can vary widely for various locations on the globe, especially areas where low clouds with large physical thickness values are dominant (e.g., Stratus clouds).
- Available bandwidth can vary widely within the same class of clouds between tens of KHz to several GHz.
- Appropriate transmission schemes is needed to accommodate such a wide variations.

Increased Link Availability using Fractal Modulation on Ultra-short Laser Pulses

- Transmission spectral efficiency is kept over a broad range of rate-bandwidth ratios using a fixed transmitter configuration.
- Redundant copies of the transmitted data are provided across the time-frequency plane.
- A form of multi-rate communication diversity.



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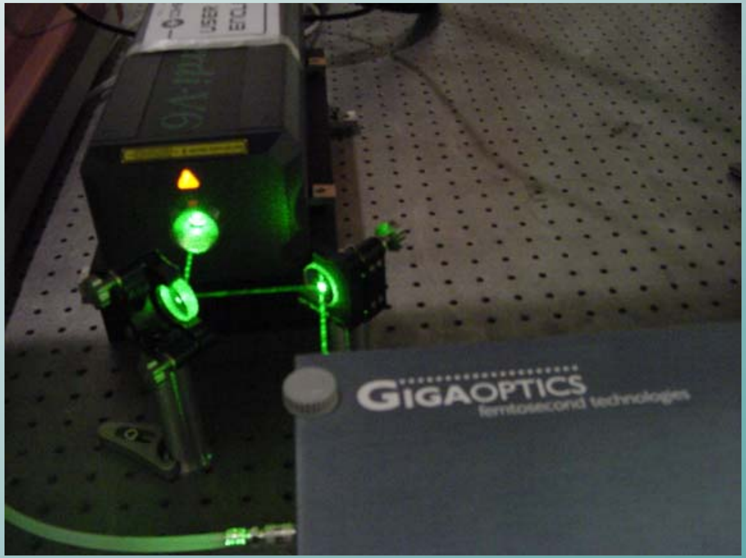
Ultra-short Pulse Laser Technology

- Ultra-fast switching times and ultra-high transmit powers enable communication capabilities that far exceed anything available today.

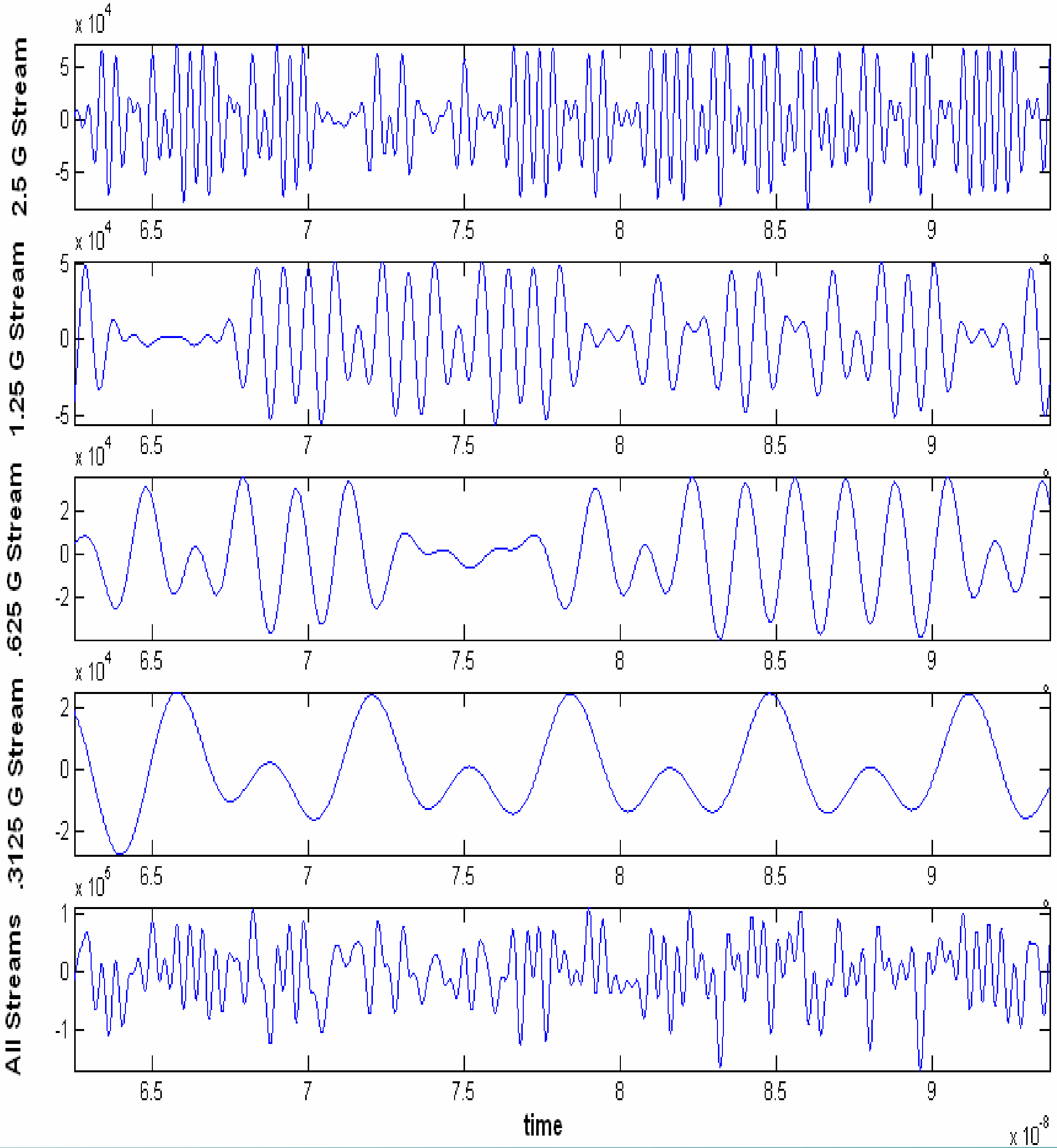
- A 100 fs pulse at 100 mJ would produce a peak power of 1 Terawatt. At 2 Giga pulse per second, this is 500 watts of average power.

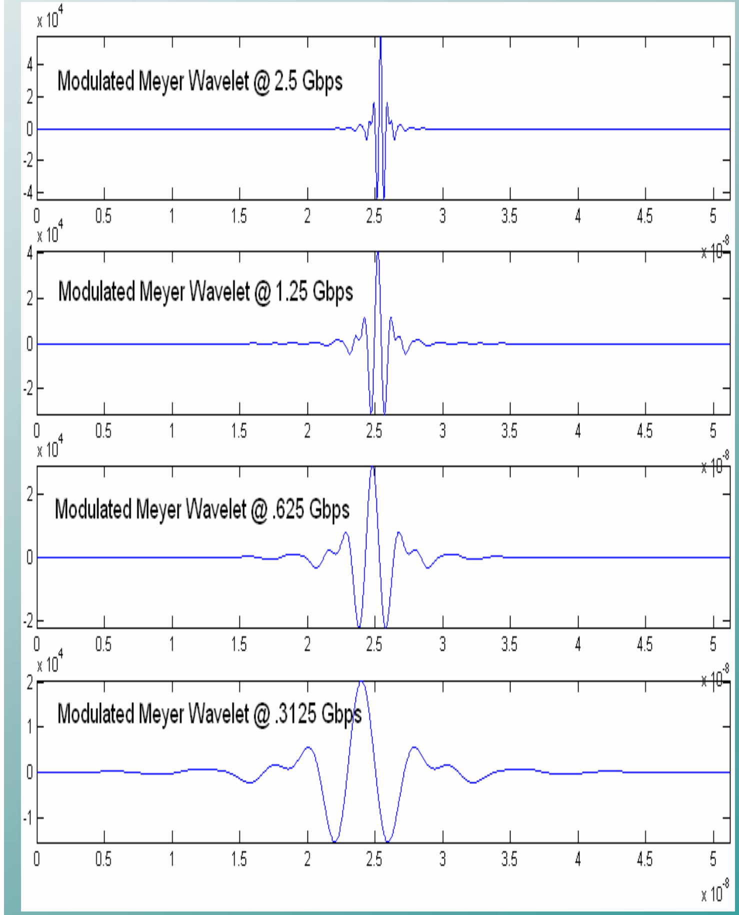
- Research into high speed ultra-short pulsed lasers and their interaction with matter indicate there may be opportunities using extremely short pulse-shaped techniques to condition the molecular interactions in order to reduce absorption. Reduced loss of laser energy due to atmospheric attenuators would be a vital element in the expansion of FSO based communications.

- Ultra-short pulses shaped through signal processing can help penetration thru clouds.

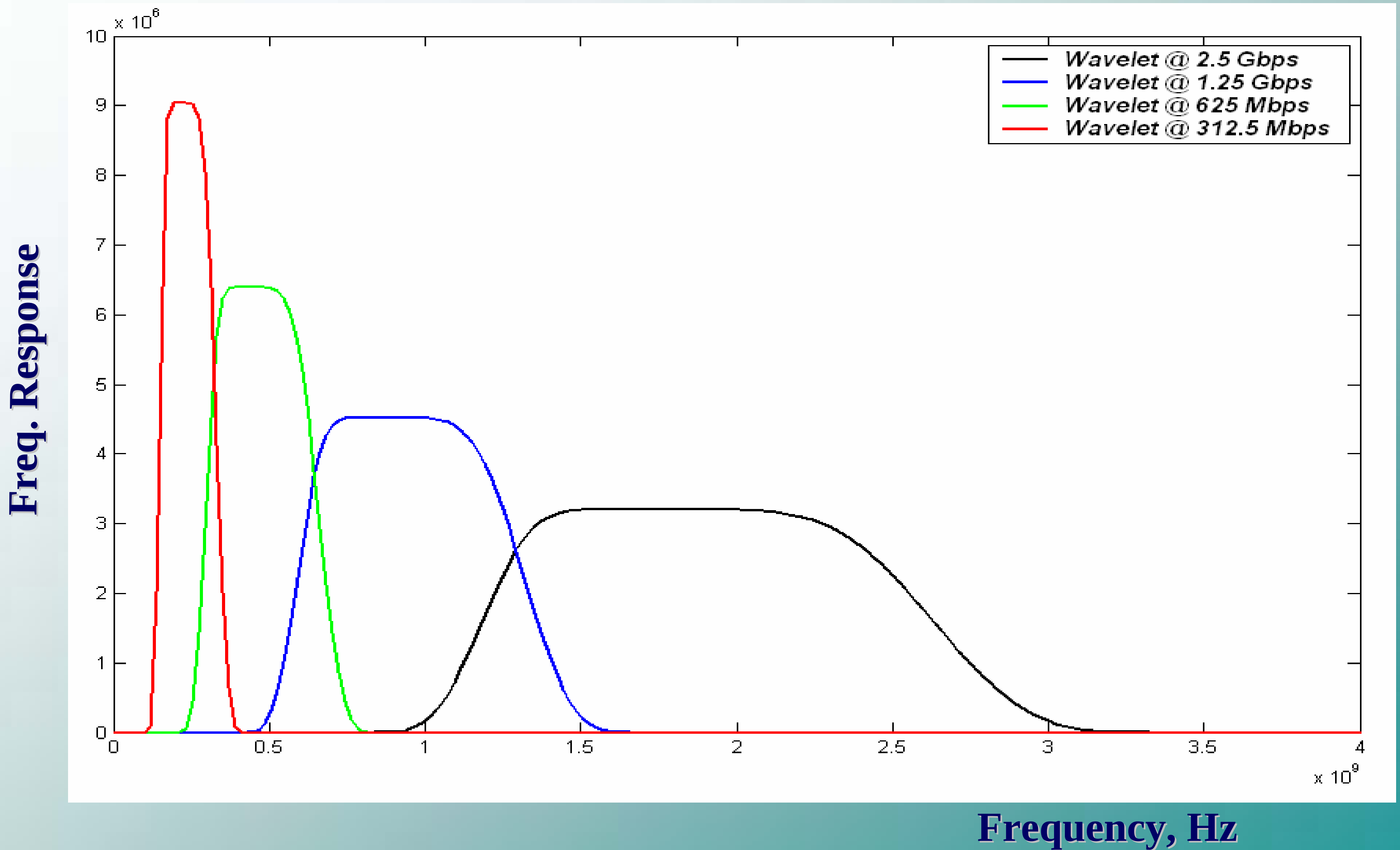


Modulated Meyer's Wavelets



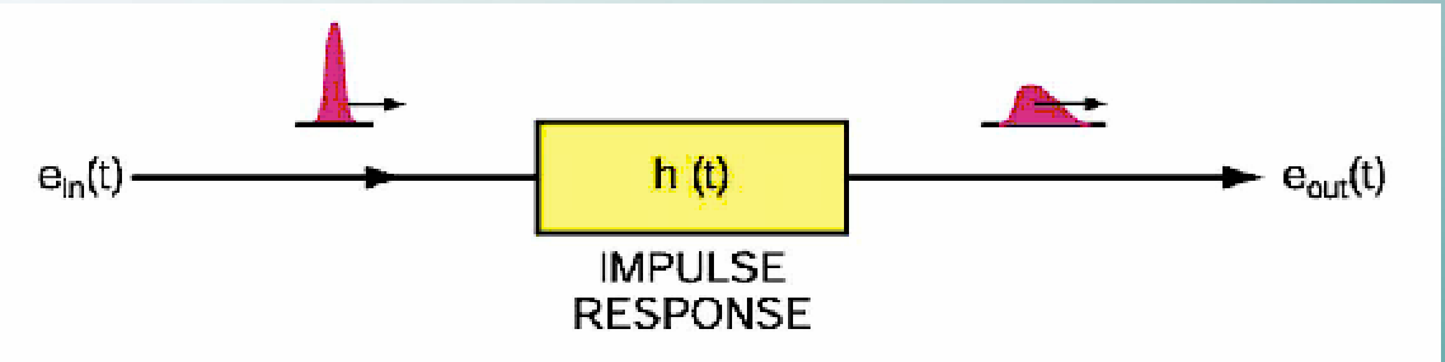


Meyer's Wavelets

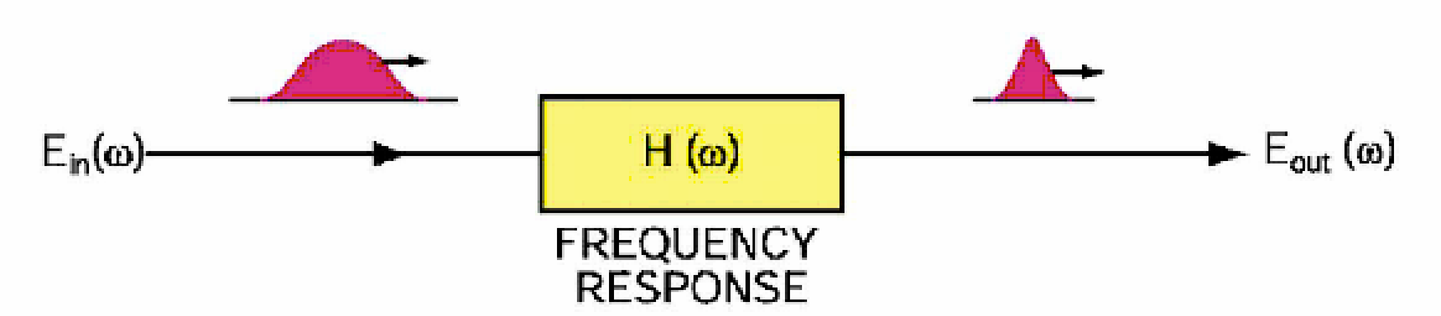


Pulse Shaping by Linear Filtering

Time Domain $$e_{out}(t) = \int dt' h(t-t')e_{in}(t')$$

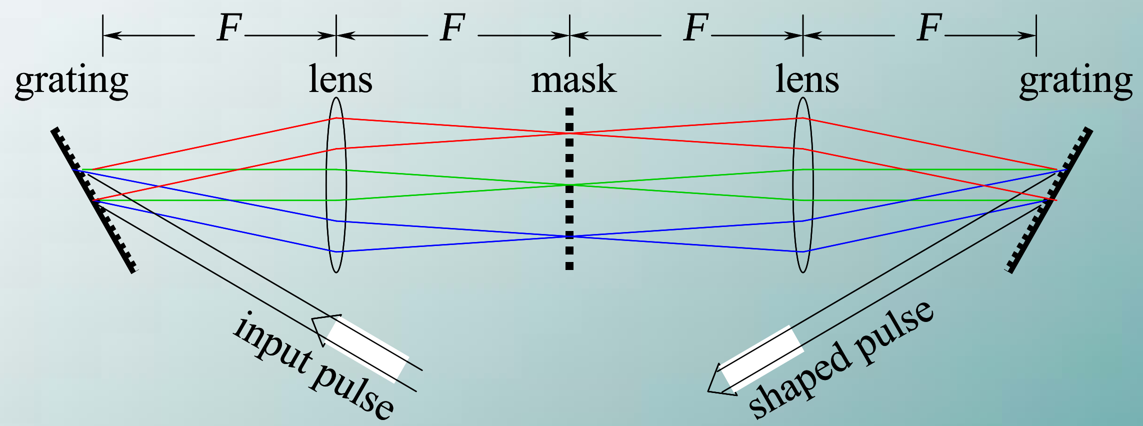


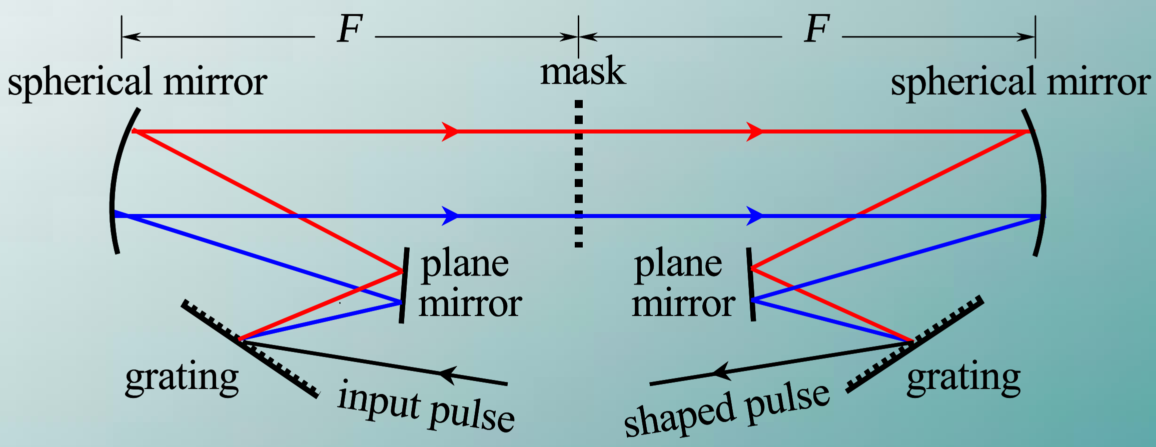
Frequency Domain $$E_{out}(\omega) = H(\omega)E_{in}(\omega)$$



Pulse Shaping by Linear Filtering

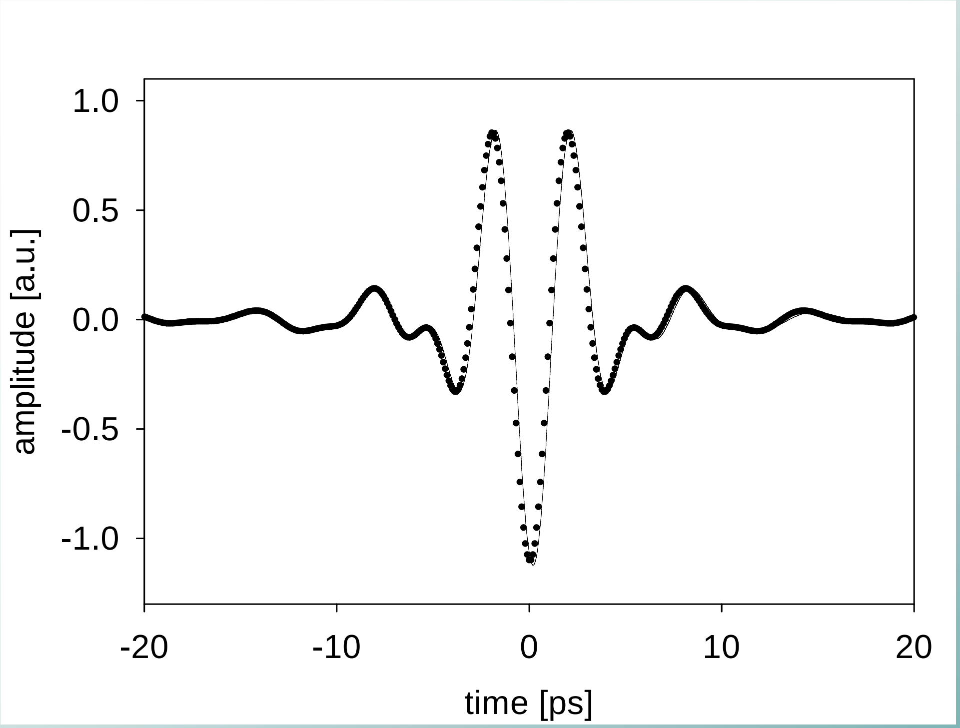
Pulse shaping apparatus

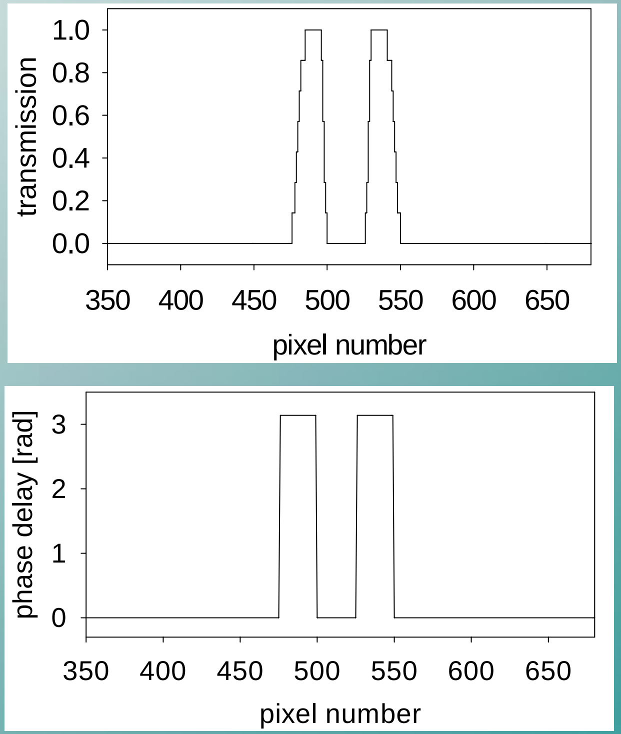




Sample Waveforms

Meyer wavelet of order 4



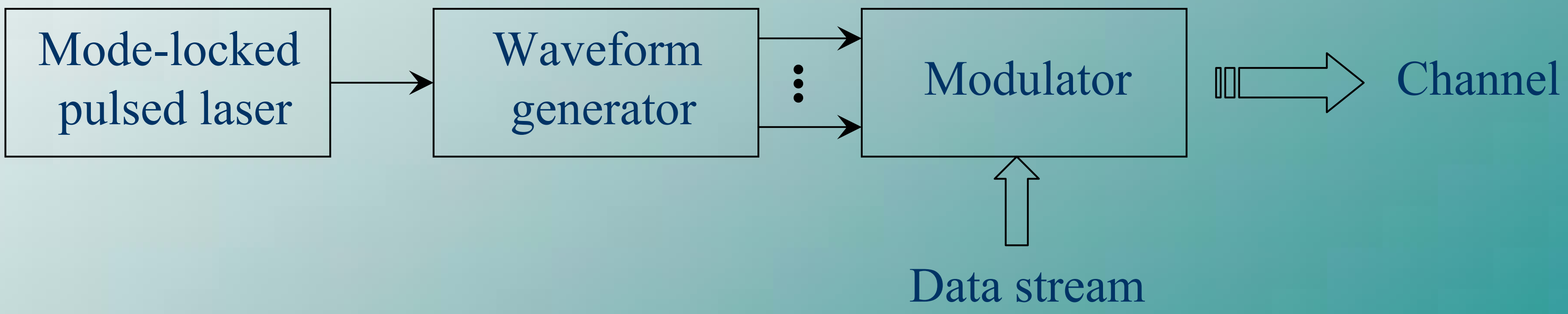


Mask complex transmission

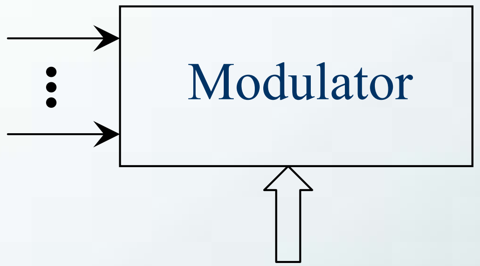
Multi-Rate Encoder

Goal: N rates over a single laser beam

Approach: Generate N waveforms and modulate each at a different data rate.

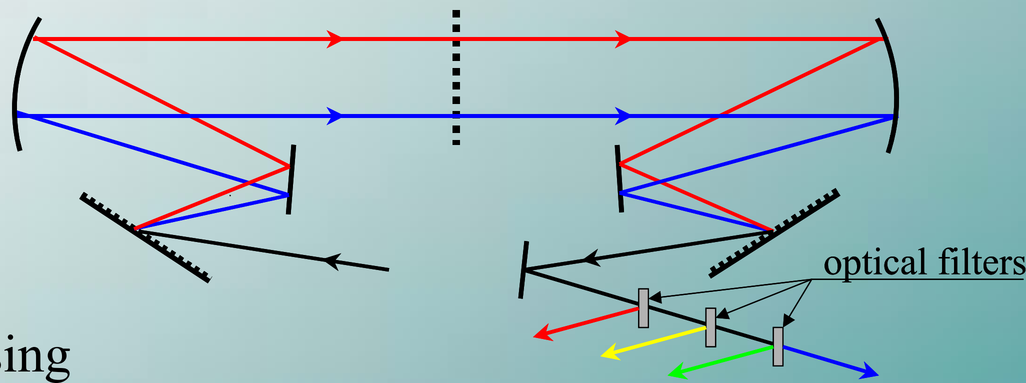


Multi-Rate Encoder

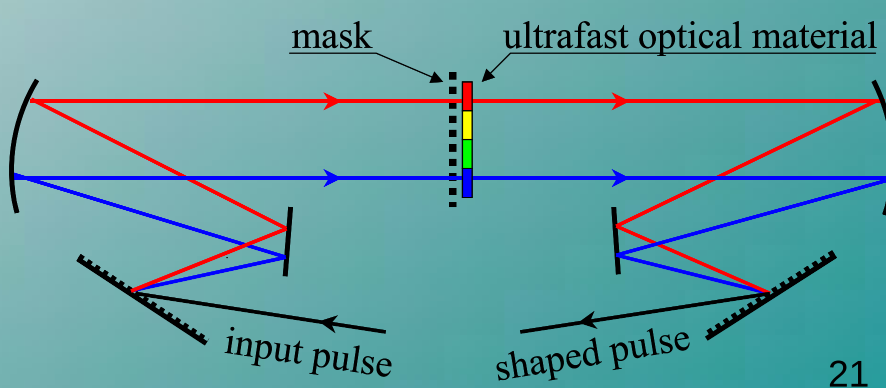


Where and ***How*** to modulate with data?

- After the pulse shaper using optical filters and conventional optical gates/switches?



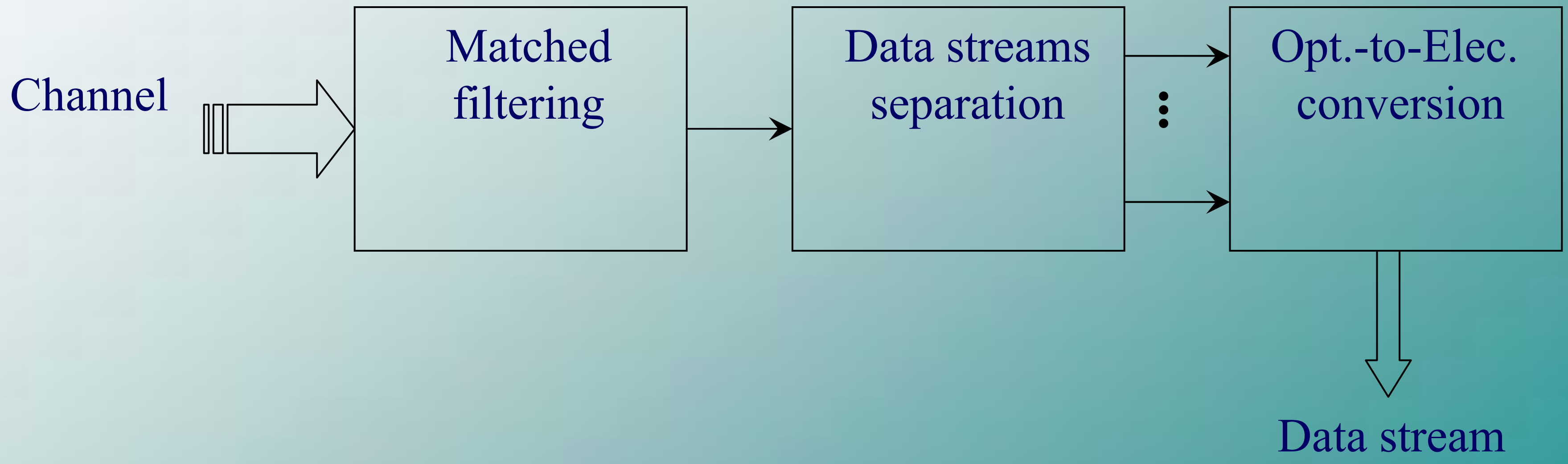
- Within the pulse shaper using new ultra-fast optical materials.



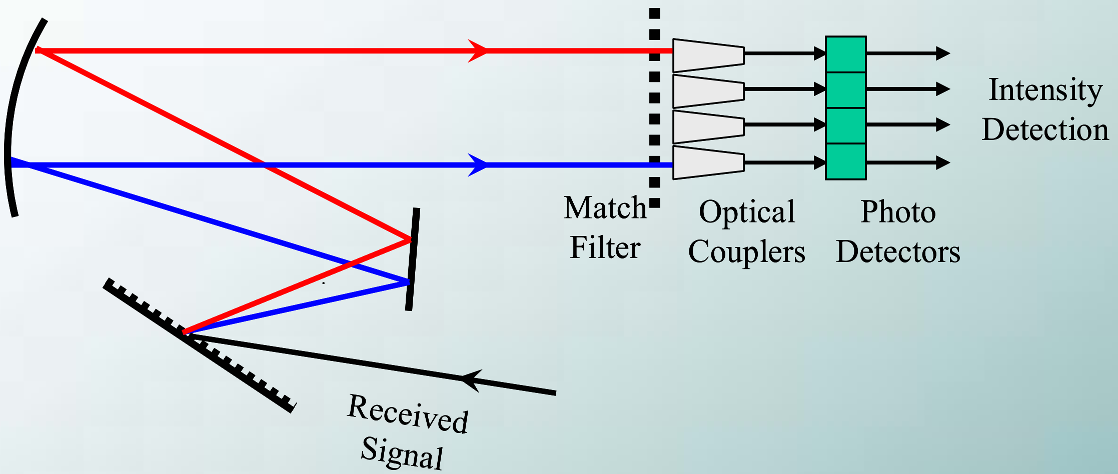
Multi-Rate Decoder

Goal: Retrieve N rates from a single laser beam

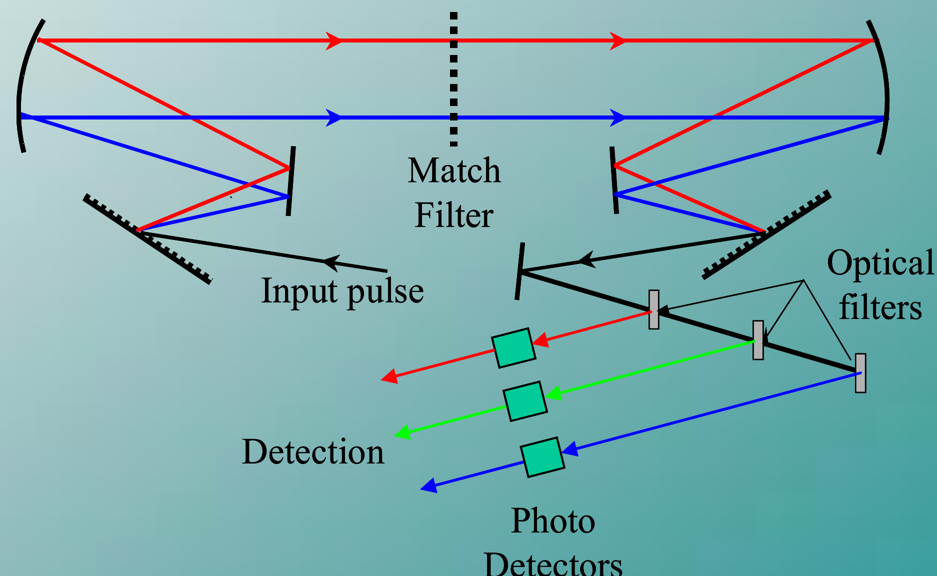
Approach: Optical matched filtering plus spectral filtering



Multi-Rate Decoder



Mask plane
Data stream separation



Data stream separation using optical filters

System Performance

- Use simulation test bed to evaluate system performance
- Integrate results from pulse shaping in the system evaluations
- Simulation parameters:

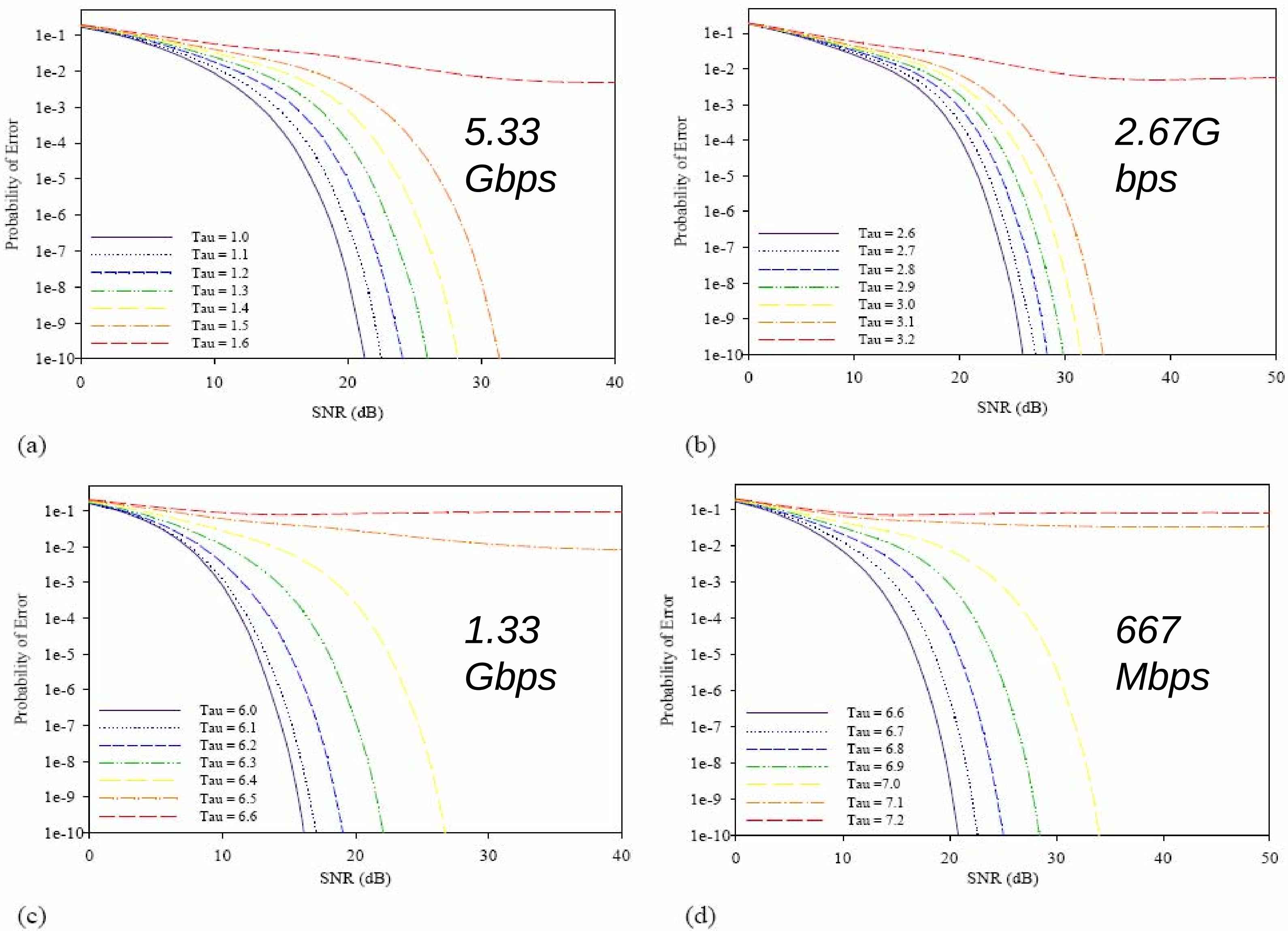
  Modulation scheme: Multi-Rate Multi-Wavelength

  Rates: 5.33 Gbps, 2.67 Gbps, 1.33 Gbps, 667 Mbps

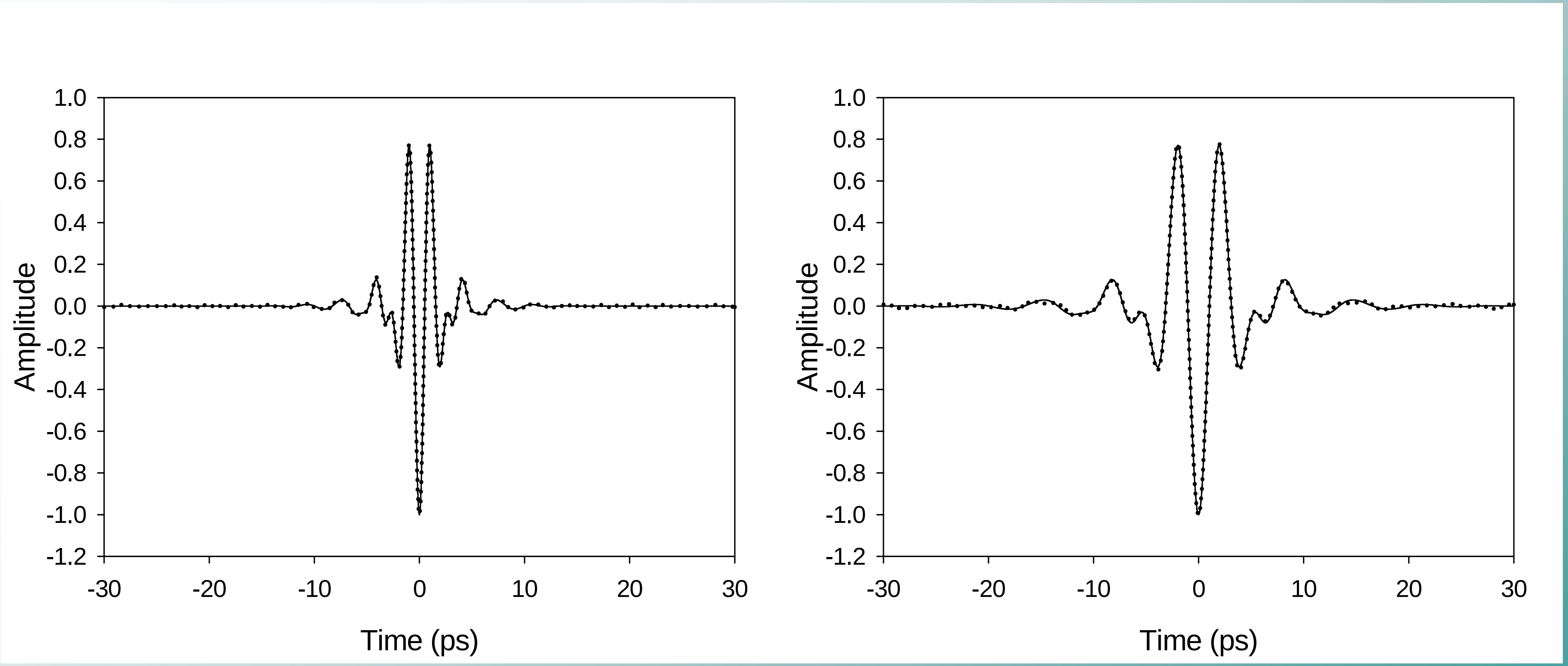
  Total Rate: 10 Gbps

  Pulse Shapes: Ultra-short Meyer Wavelets
  Channel: 1 Km, varying optical thickness

BER System Performance - NRZ

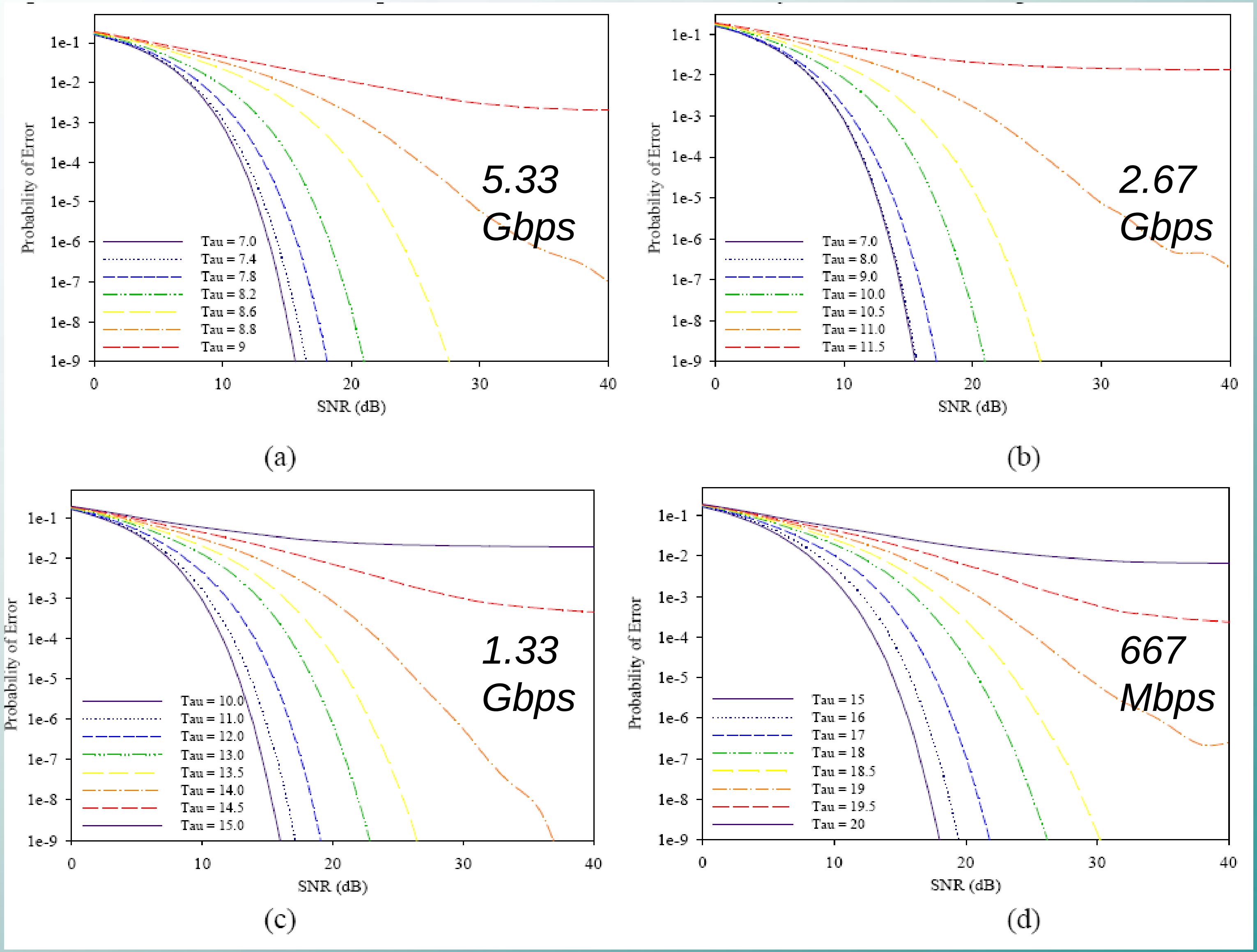


Evaluated Pulses



5.33 Gbps	1.33 Gbps
2.67 Gbps	667 Mbps
(20 ps)	*(40 ps)*

BER System Performance - RZ



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Summary

- Substantial bandwidth is available for communication during typical meteorological conditions, even in the presence of clouds.
- Appropriate modulation schemes have to be adopted to handle the wide variations in channel conditions.
- Wavelet multi-rate system exhibits a better performance in comparison to conventional single rate systems.
- Short-pulsed systems offer a higher resilience against cloud obscurations.